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Bulk Metallic Glasses - Characteristics and Possibilities

Eldrup, Morten Mostgaard; Byrne, Cormac

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Bulk Metallic Glasses –

Characteristics and Possibilities

Morten Eldrup and Cormac Byrne

Materials Research Division

Risø DTU
National Laboratory for Sustainable Energy

Overview

- What is a metallic glass
- How to make a metallic glass and a
- Bulk Metallic Glass (BMG)

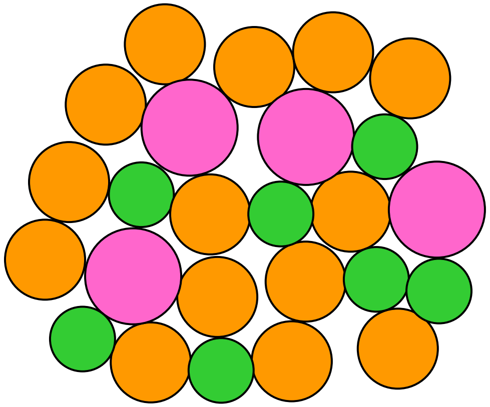
- Some properties of BMGs
  - Supercooled liquid range
  - Surface imprinting
  - Forming in 3D
  - Problems
  - Near-net-shaping
  - Mechanical properties

- Conclusion

What is an amorphous alloy/metallic glass?

Glass

Solid where the atom positions are disordered



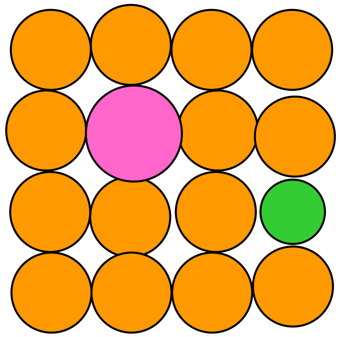
Ceramic

Polymer

Metallic

Crystal

Solid where the atom positions are ordered



Ceramic

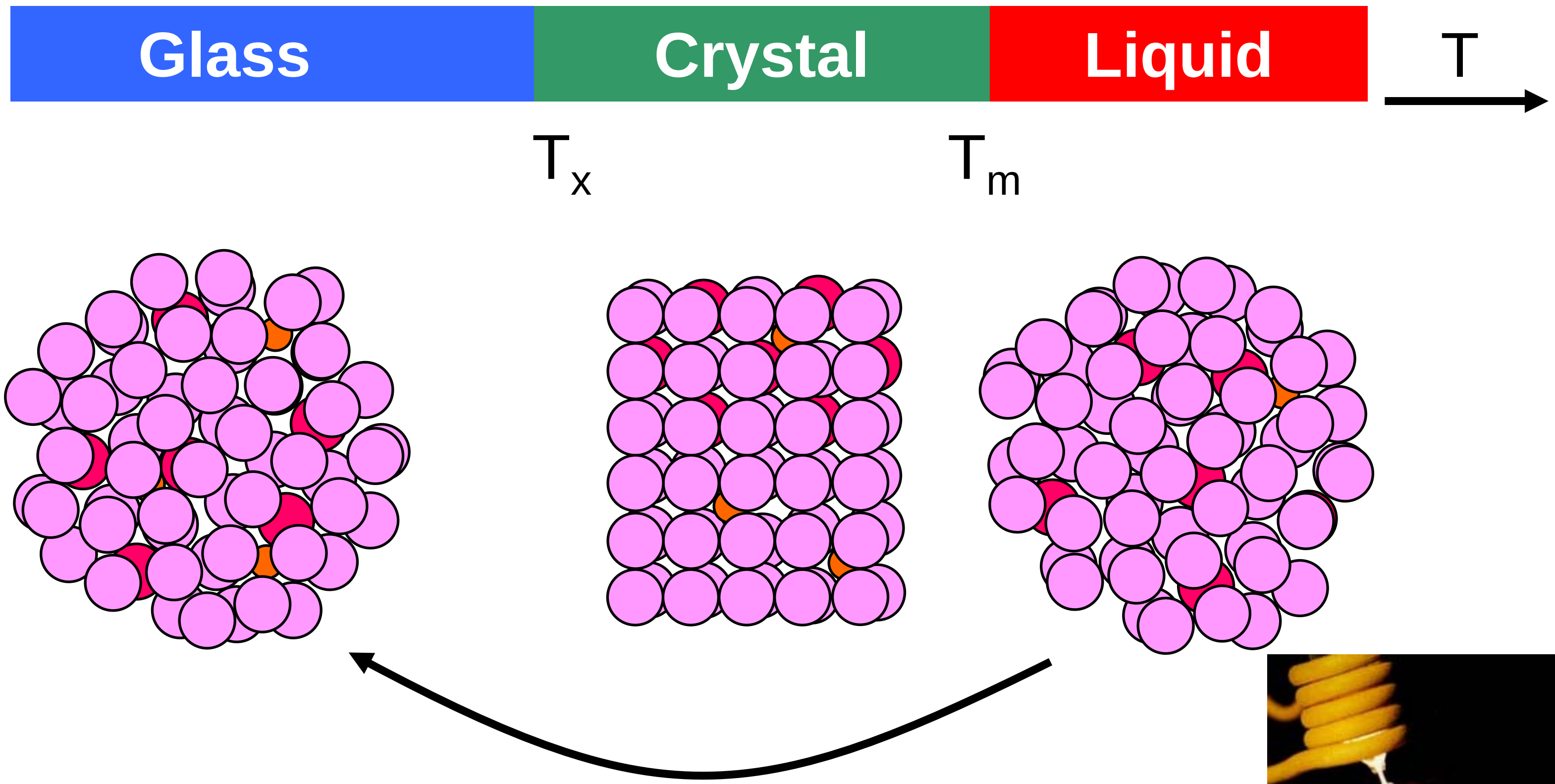
Polymer

Metallic

Discovery of metallic glasses

1959 First report of rapid cooling of a metallic alloy to form a glass
Paul Duwez, California Institute of Technology, USA

Metallic glass



Rapid cooling ~ 10^6 K/s
Results in thin ribbons

MIKROMETAL

Discovery of metallic glasses

1959 First report of rapid cooling of a metallic alloy to form a glass
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1970s Magnetic applications of rapidly cooled metallic glasses
Electrical transformers, antitheft strips

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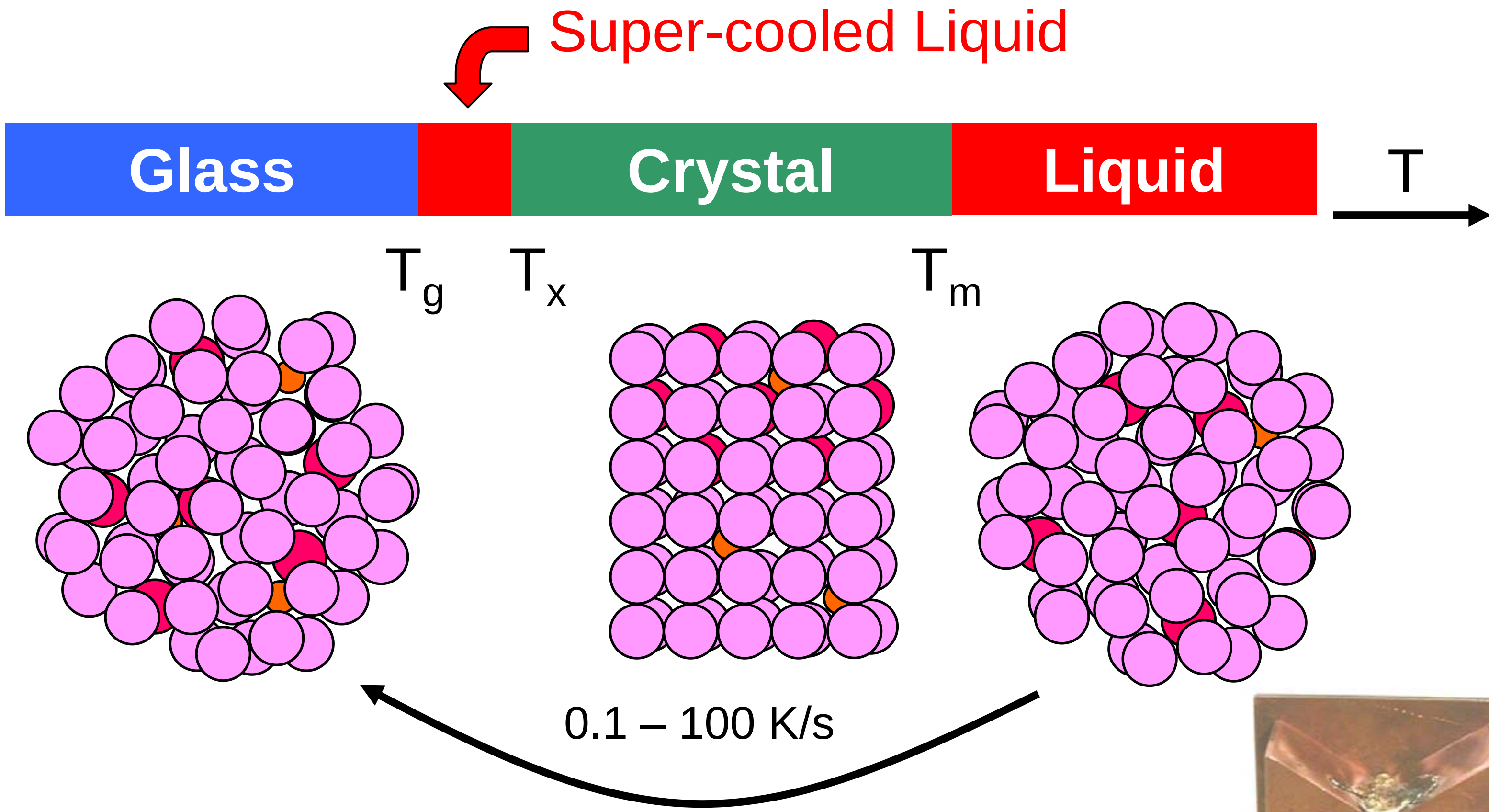
1970s Magnetic applications of rapidly cooled metallic glasses
Electrical transformers, antitheft strips

1984 First report of metallic alloys that avoid crystallization without rapid cooling by Kui et al., Harvard University, and Akihisa Inoue et al., Tohoku University, Japan (1989)

Bulk metallic glass = **BMG**

Bulk Metallic Glass



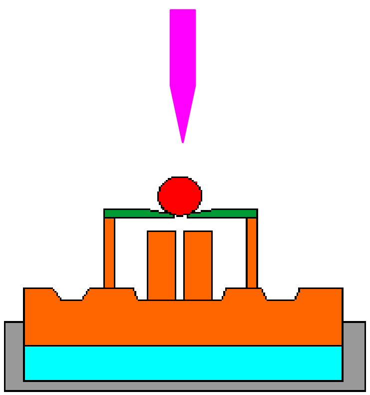
Moderate cooling rate is
sufficient to avoid crystallisation


MIKROMETAL

Making BMG Castings

Drop casting in arc melter ~4 g

Rods 3 - 5 mm Ø, 25 mm long



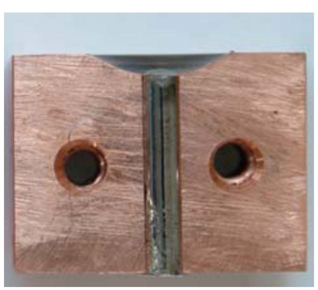
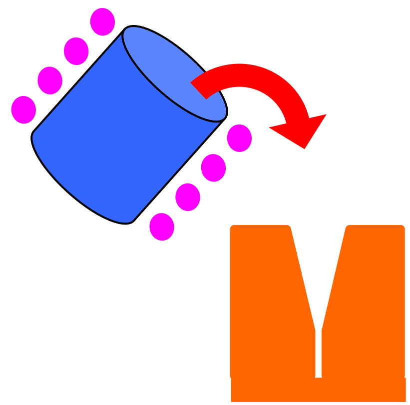


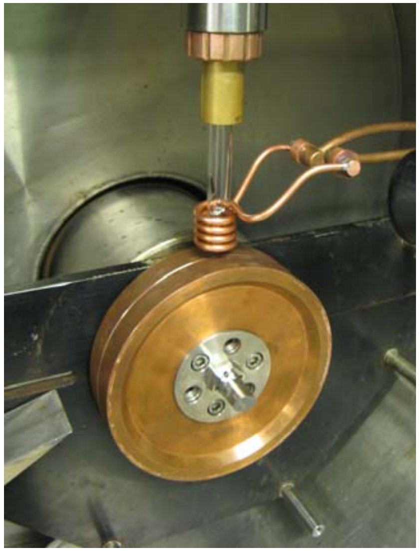
Plate casting in induction melter ~ 10 g

25 x 25 x 2 mm^3 plates



Ribbon Spinning ~ 3 g

70 µm x 4 mm x 3 m

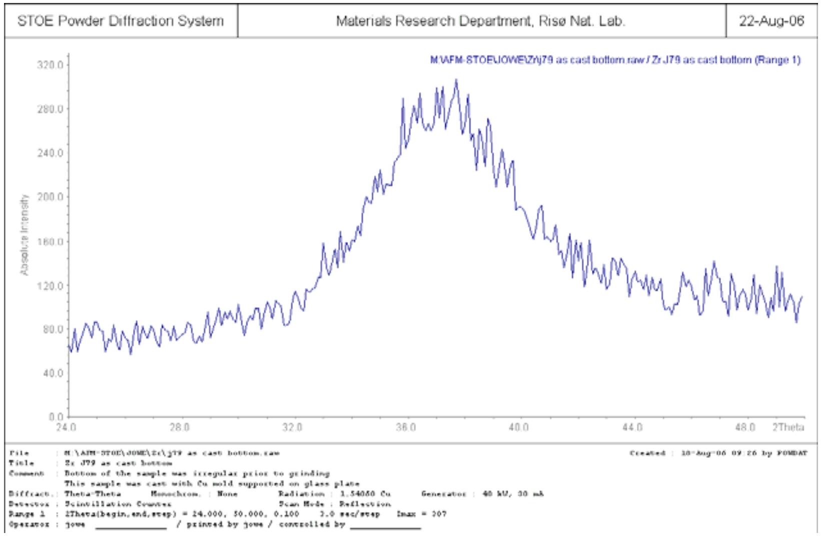


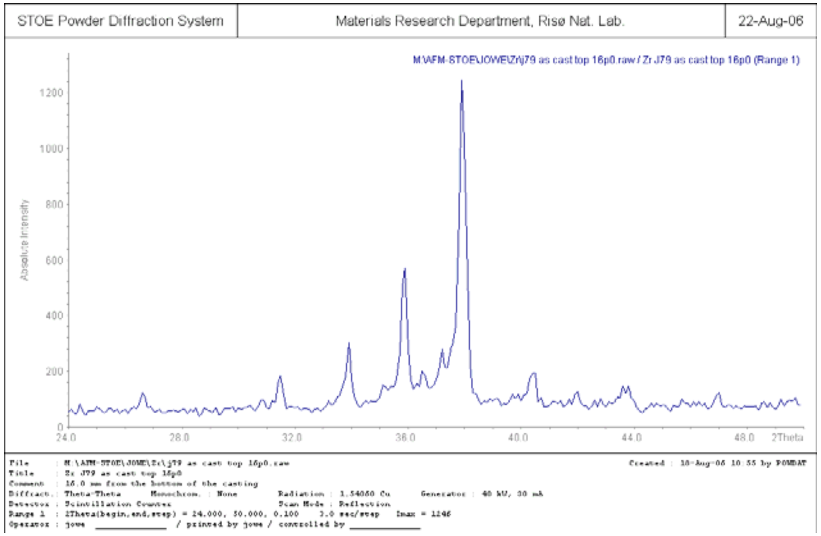
MIKROMETAL

Specimens produced by melt spinning, drop casting or suction casting

1 mmØ

- No visual difference between amorphous and crystalline casting
- Check castings by x-ray



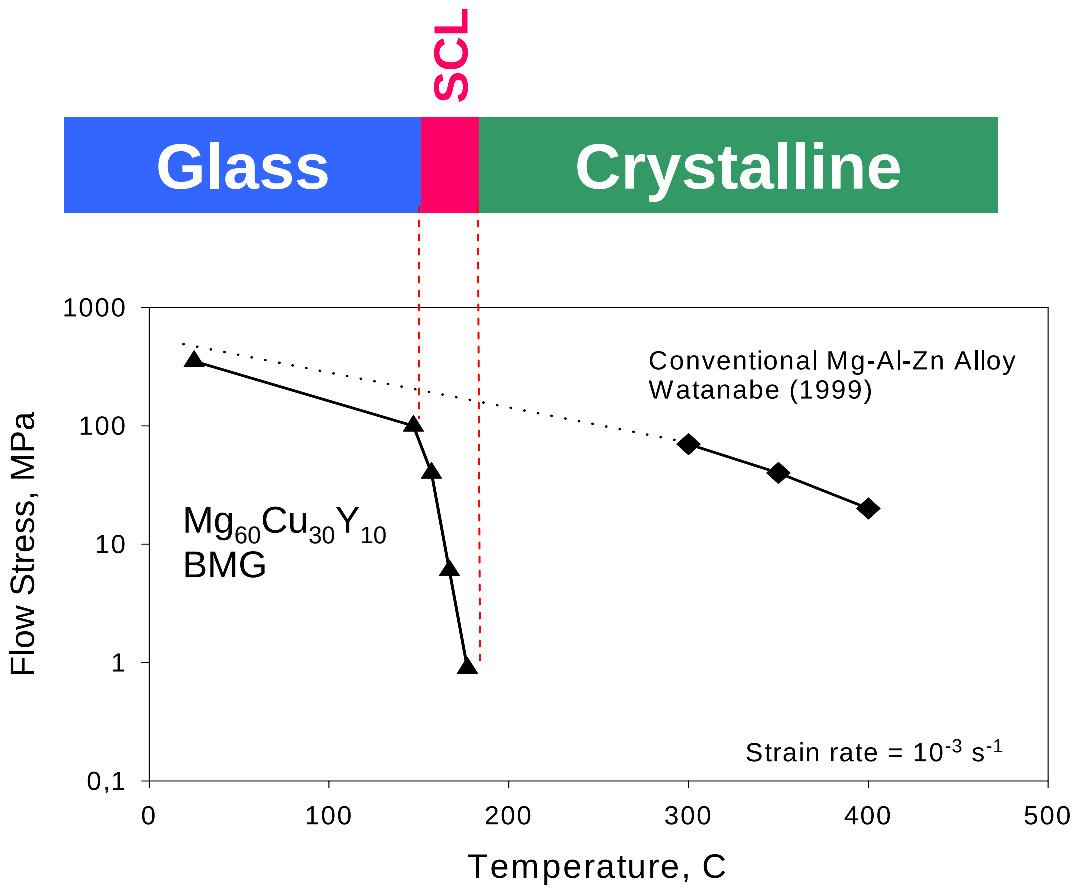


Examples of BMG

Alloy Family	Specific alloy	Critical cooling rate (K/s)	T_g (K)	T_x (K)
Ti-Zr-TM	$Ti_{34}Zr_{11}Cu_{47}Ni_{8}$	250	698	727
Mg-Ln-(Cu,Ni, Zn)	$Mg_{65}Cu_{25}Y_{10}$	50	425	479
Ln-Al-TM	$La_{55}Al_{25}Ni_{15}Cu_{5}$	35	474	541
Zr-Ti-Al-TM	$Zr_{52.5}Ti_{5}Al_{10}Ni_{14.6}Cu_{17.9}$	20	~700	~795
Zr-Ti-TM-Be	$Zr_{38.5}Ti_{16.5}Ni_{9.75}Cu_{15.25}Be_{20}$	2	630	678
Pd-Cu-Ni-P	$Pd_{42.5}Cu_{30}Ni_{7.5}P_{20}$	0.067	574	660

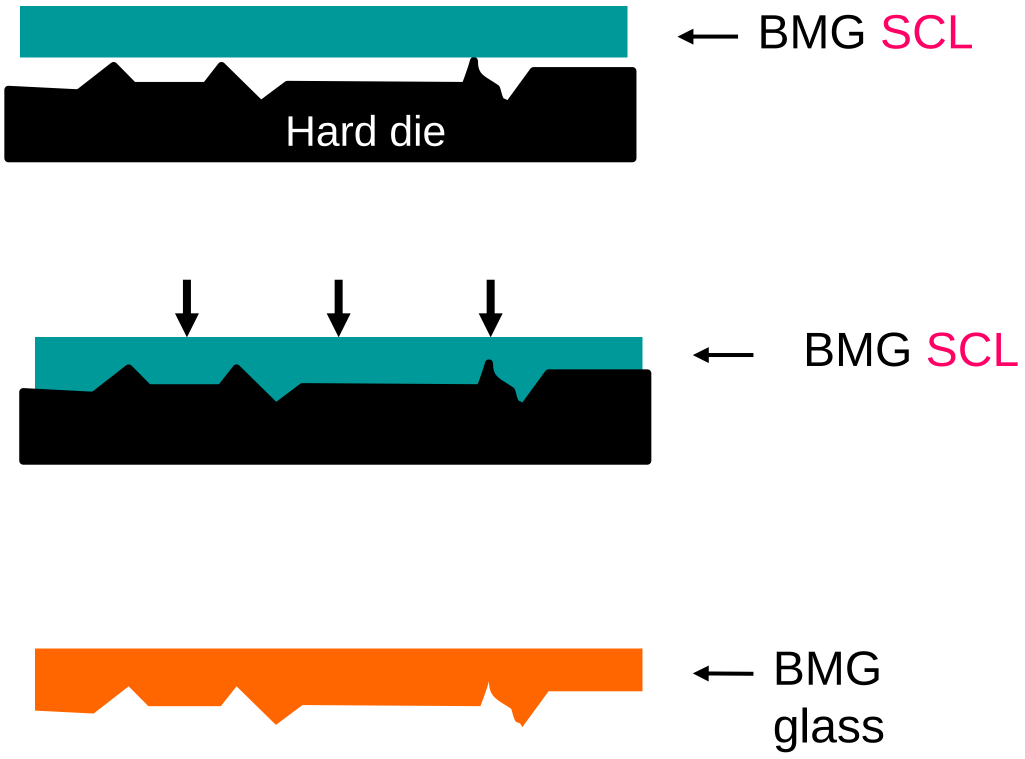
TM = Group VI–VIII transition metals (Cr, Mo, W, Mn, Re, Co, Rh, Ir, Ni, Pd, Pt)

Ln = Y, Lanthanide metals (La or rare earth metals)


SCL
Glass
Crystalline
Flow Stress, MPa
1000
100
10
1
0,1
0
100
200
300
400
500
Temperature, C
Conventional Mg-Al-Zn Alloy
Watanabe (1999)
$Mg_{60}Cu_{30}Y_{10}$
BMG
Strain rate = 10^{-3} s^{-1}

Shaping Surfaces

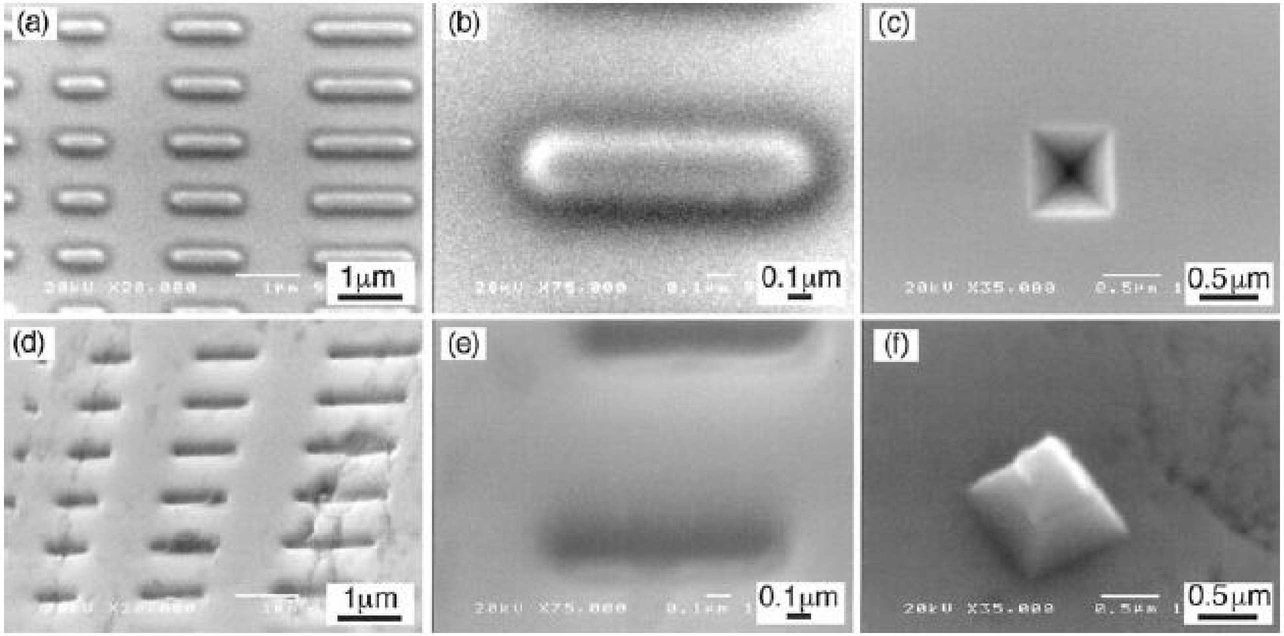
with micro- or nano-scale topology



Some patterns

Si/SiO_2 master

BMG replica

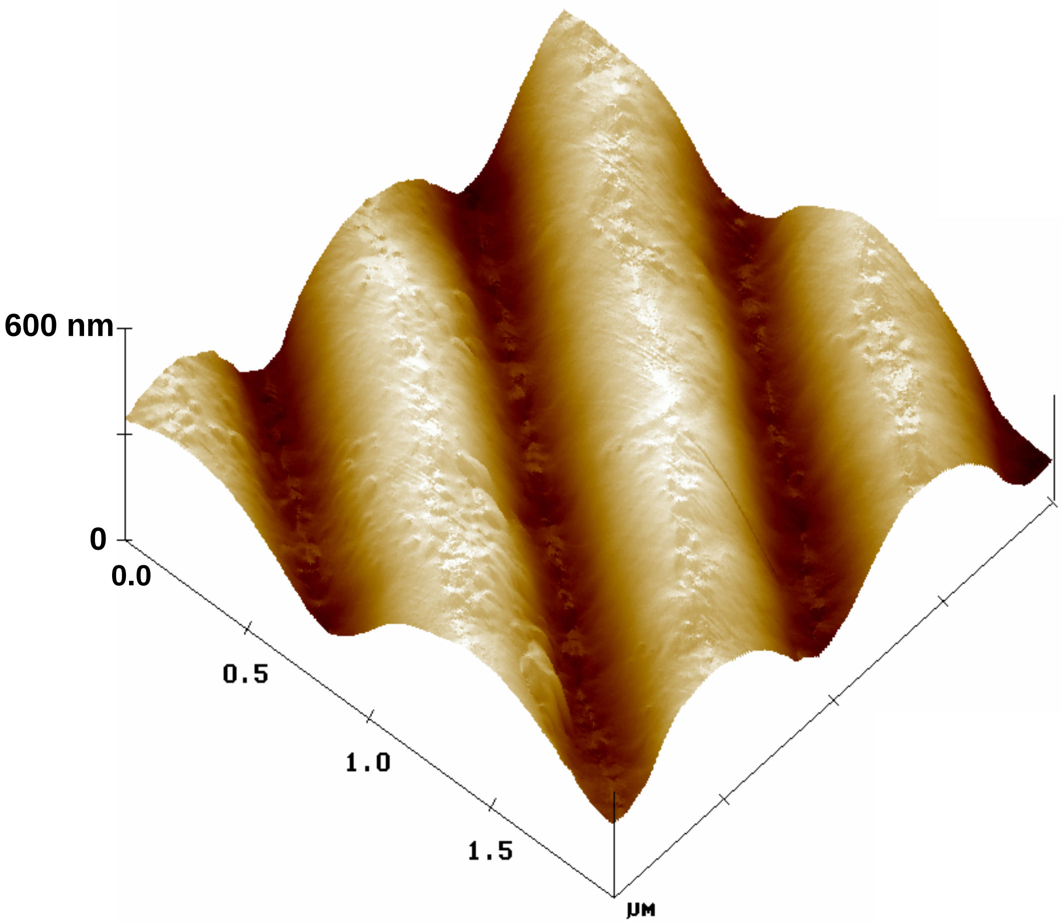


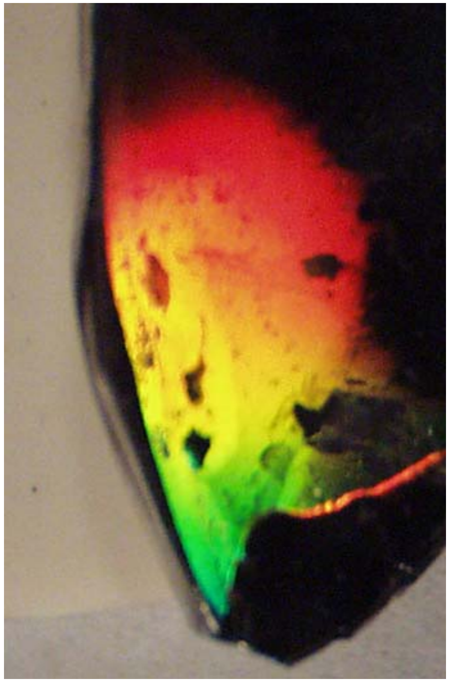
$Pd_{40}Cu_{30}Ni_{10}P_{20}$

T = 640K, P = 10 Mpa, time = 1000s

Inoue et al.

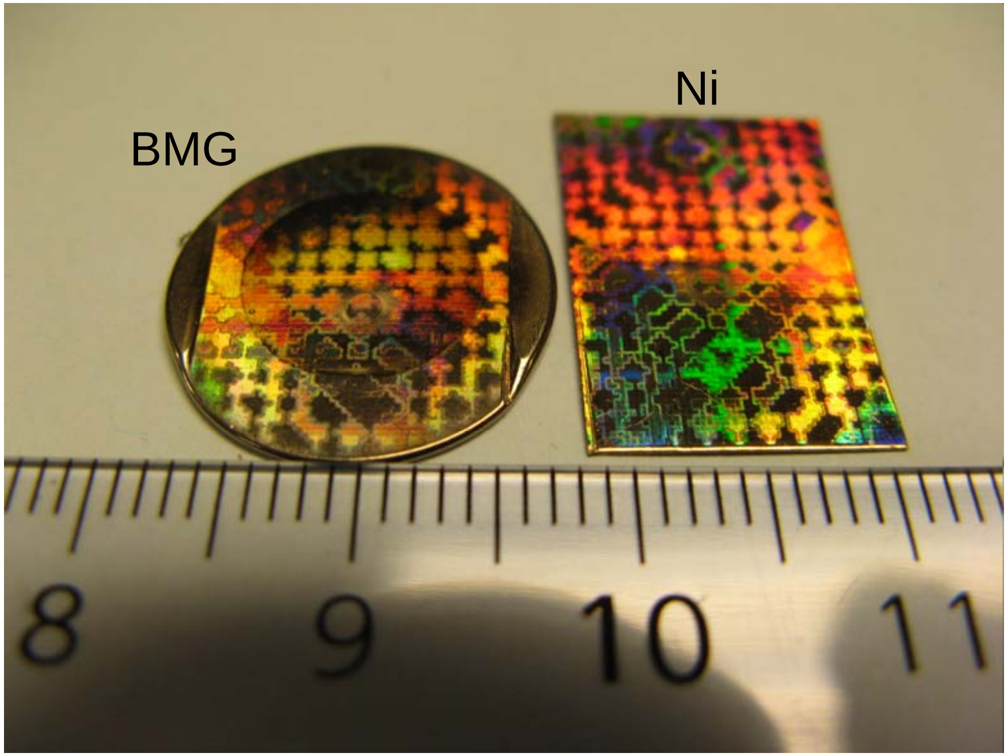
Linear sine pattern replicated on $Mg_{60}Cu_{30}Y_{10}$



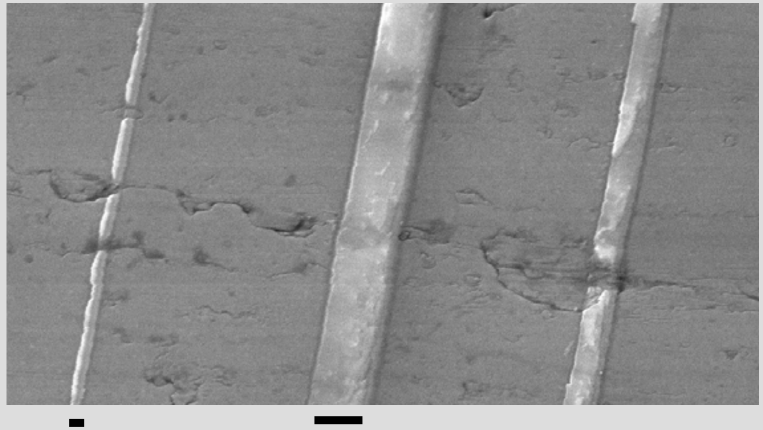


How small can these features be?

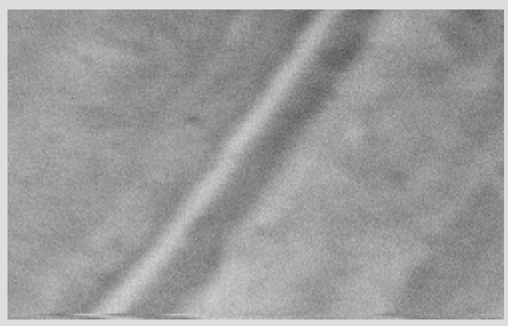
Diffraction pattern on Ni surface imprinted on a BMG ($Zr_{44}Ti_{11}Cu_{10}Ni_{10}Be_{25}$)



Nanoscale surface topology



100 nm 1 µm



12 nm

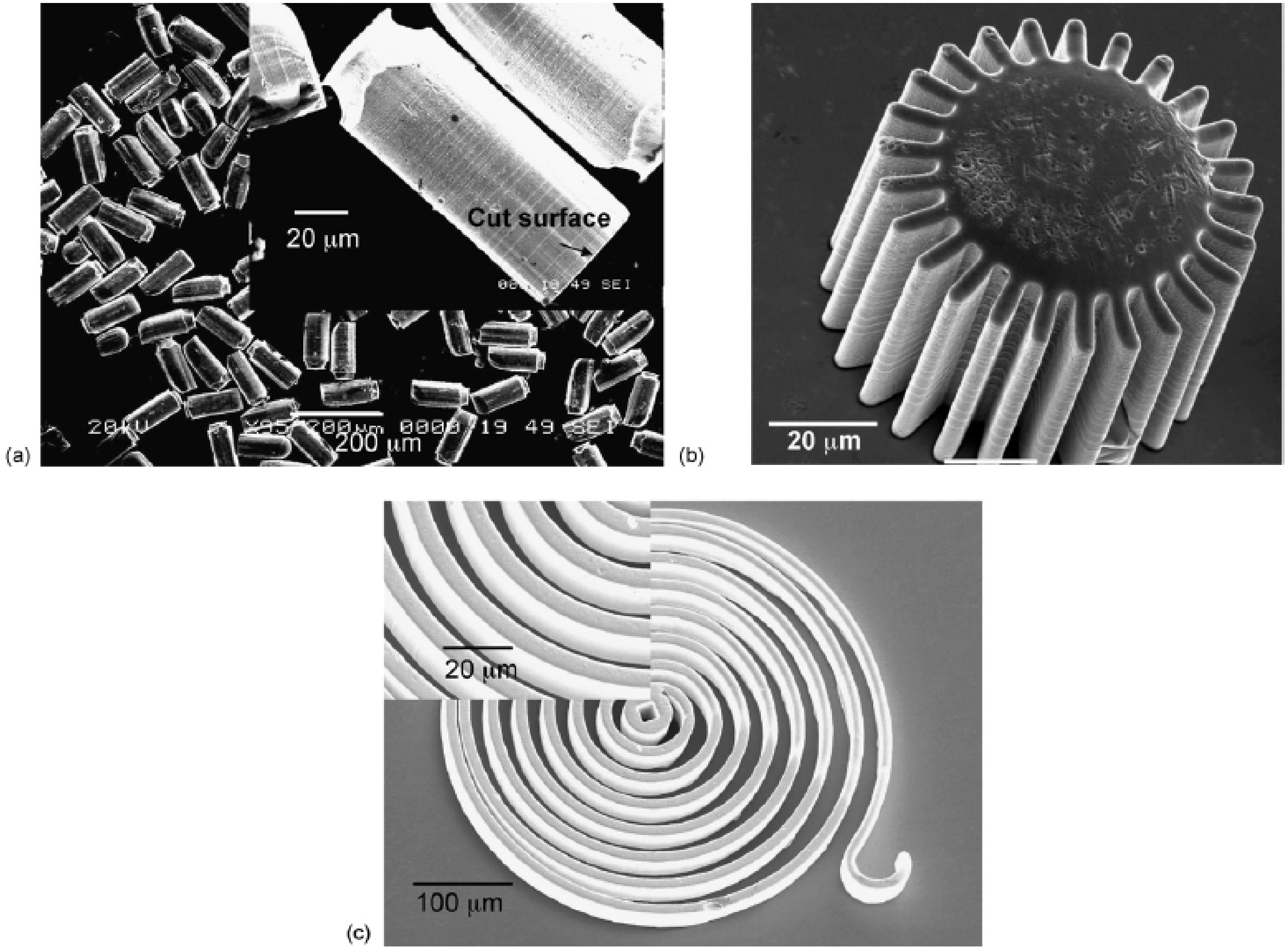
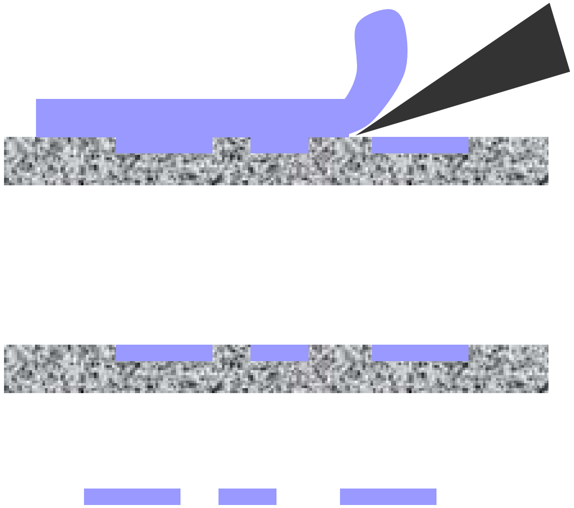
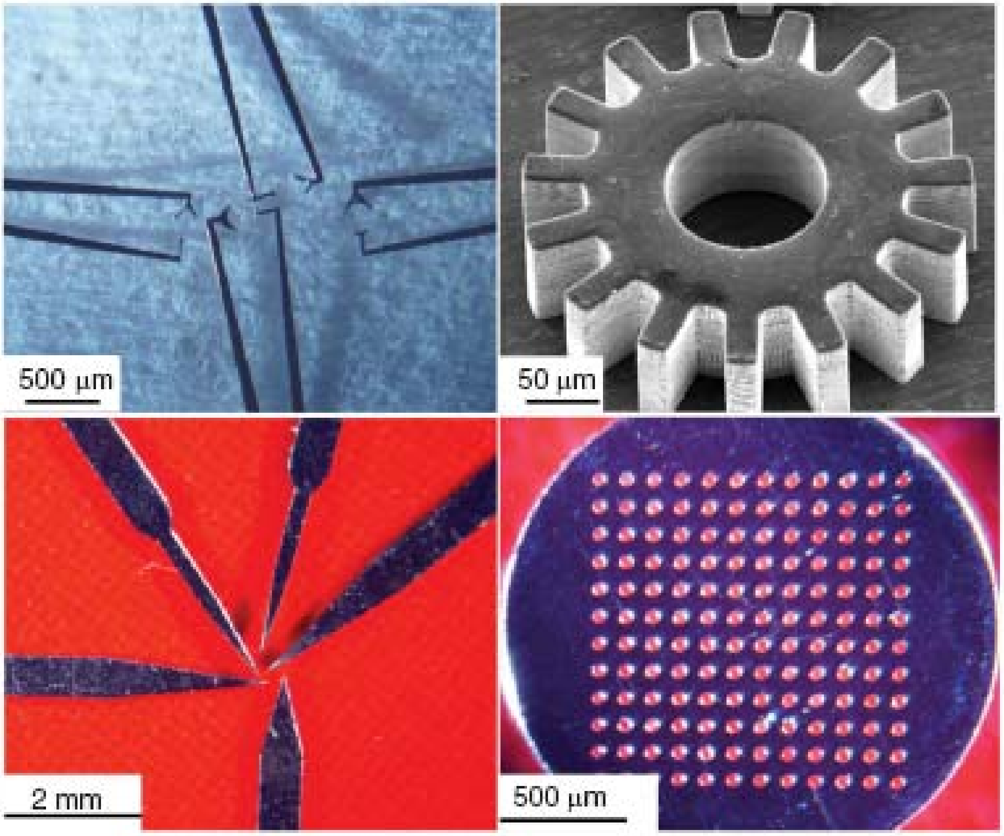


Fig. 4. Three-dimensional parts obtained by using TPF of BMG and subsequent hot-separation method. (a) Rods where the smooth cutting surface is visible. (b) Complex micro gears. (c) Coil shape spring.

Schroers et al. 2007

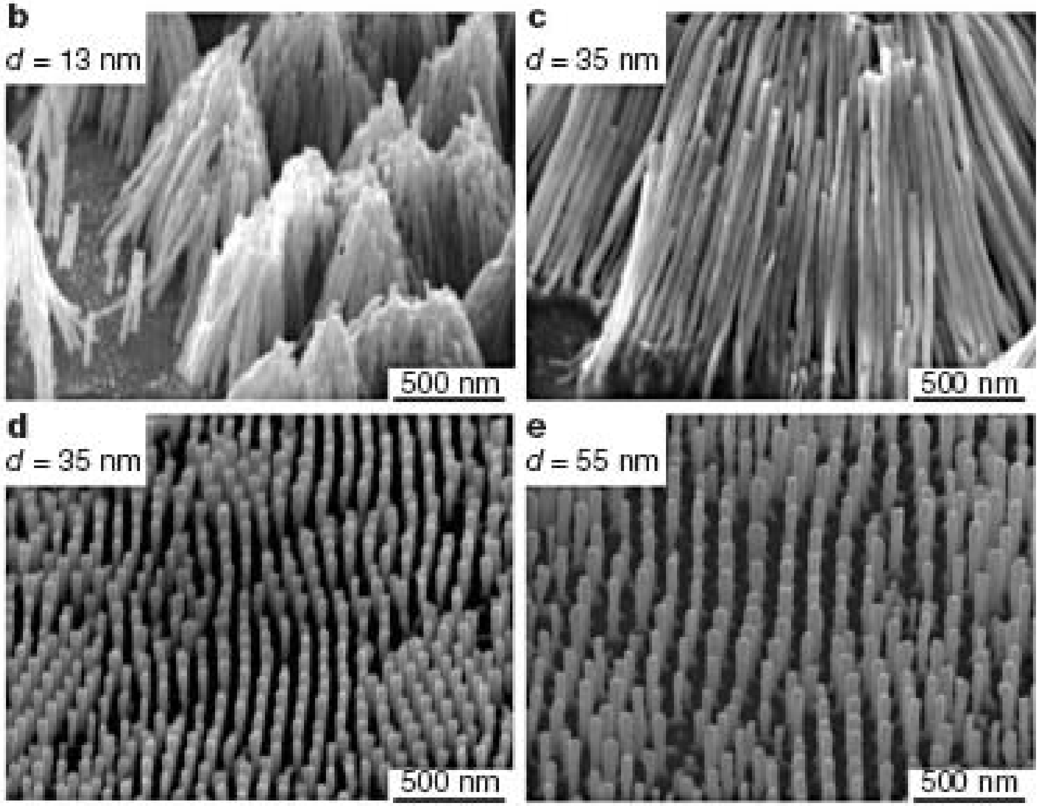
HOT CUTTING OF BMGs





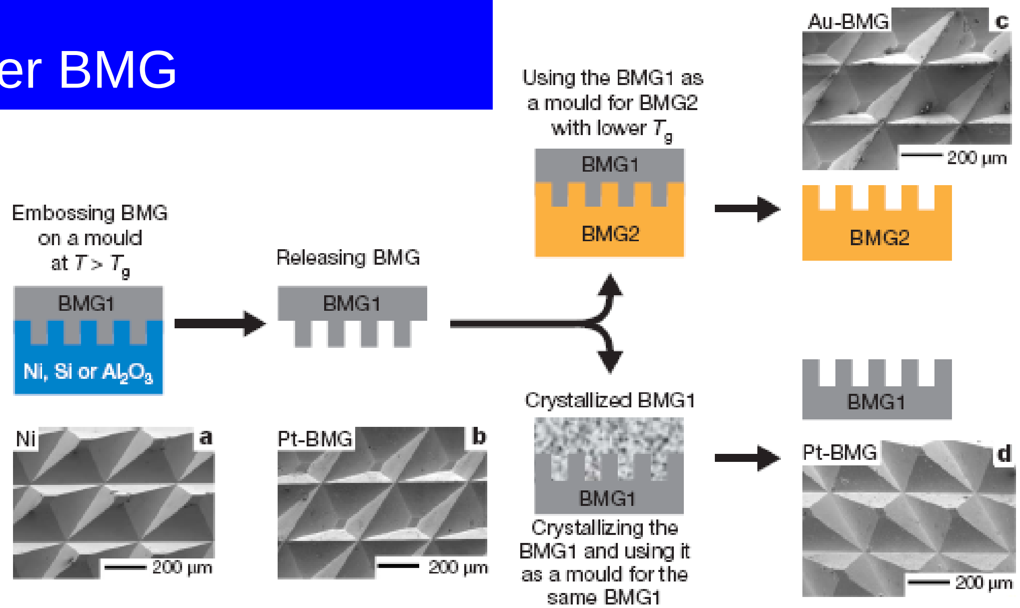
Schroers et al. 2009

Pt-BMG rods formed by embossing on porous alumina



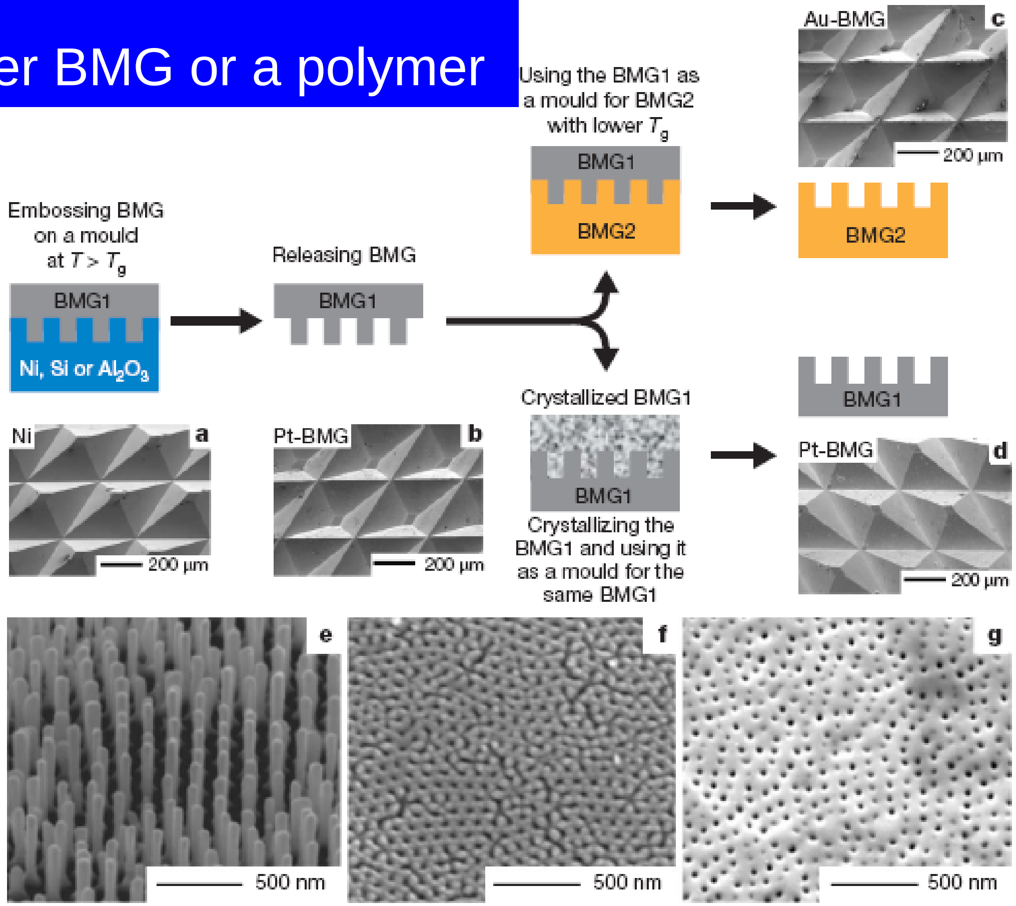
Schroers et al. 2009

Using one BMG as a mould for another BMG



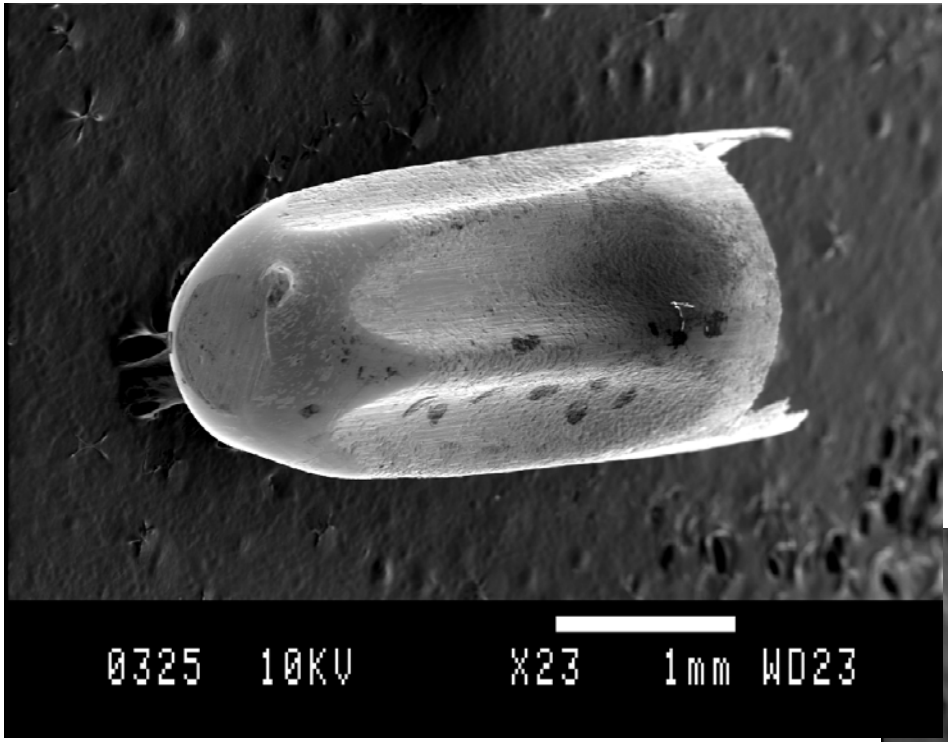
Schroers et al. 2009

Using one BMG as a mould for another BMG or a polymer

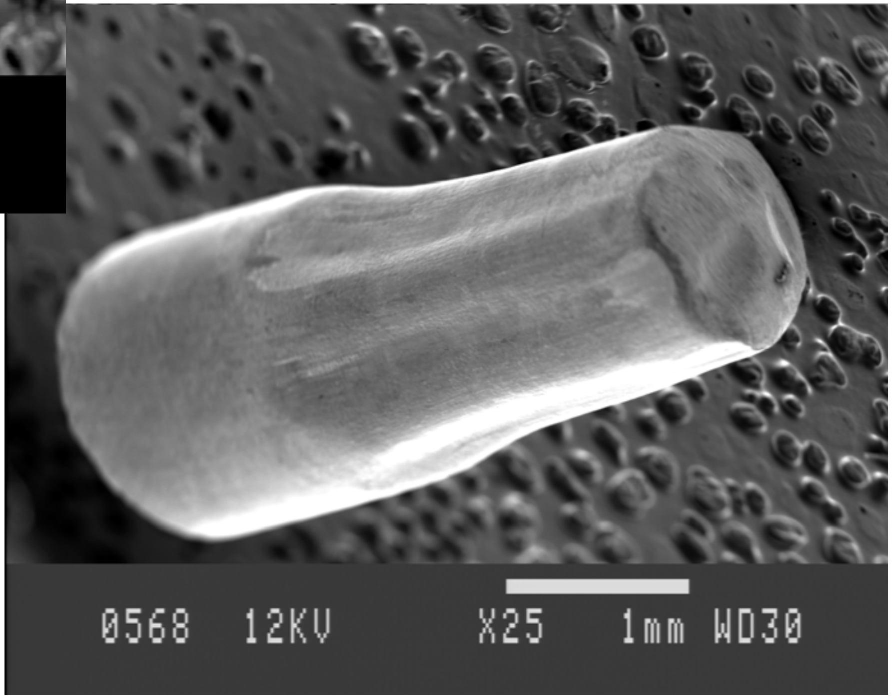


PMMA Pt-BMG

Schroers et al. 2009



BMG screwdriver tip



BMG-*material*:

Vitreloy 1B, Vit1B, LM1B

$(Zr_{44}Ti_{11}Cu_{10}Ni_{10}Be_{25})$

CTE $\sim 10\times10^{-6}$/K

T_g ~350°C

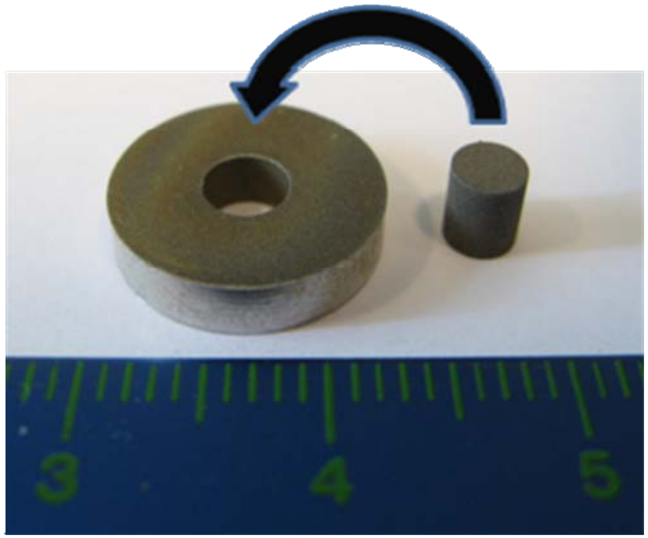
T_x ~470°C

Ejection Experiment

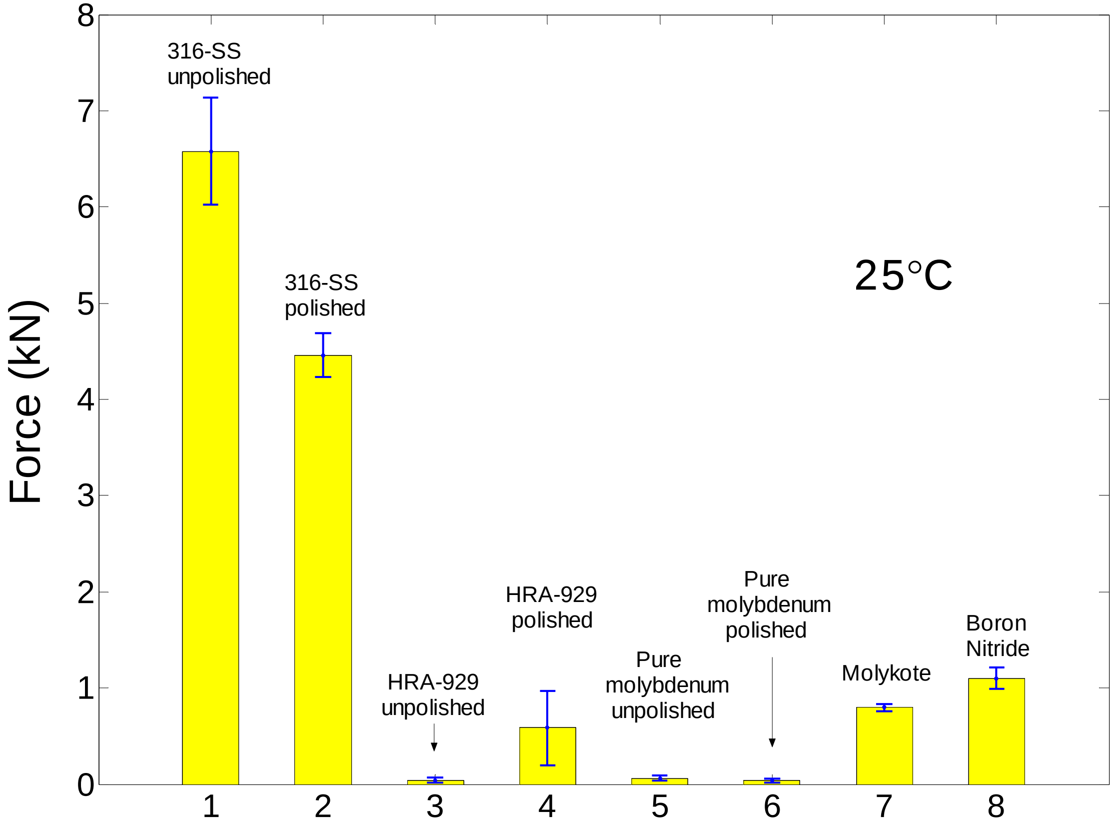
Dies with different thermal expansion coefficients:

- Stainless steel (CTE $\sim 18\times10^{-6}$/K)
- Pure molybdenum (CTE $\sim 5\times10^{-6}$/K)
- HRA-929 superalloy (CTE $\sim 6\times10^{-6}$/K) (Hitachi)

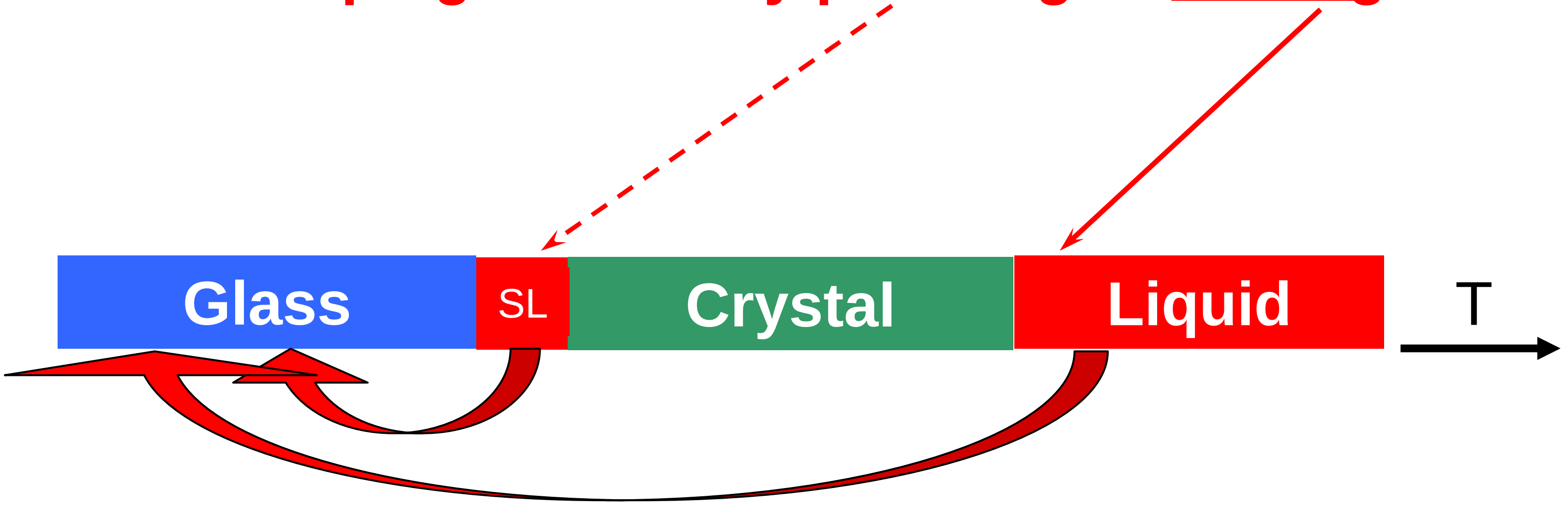
Polished and un-polished

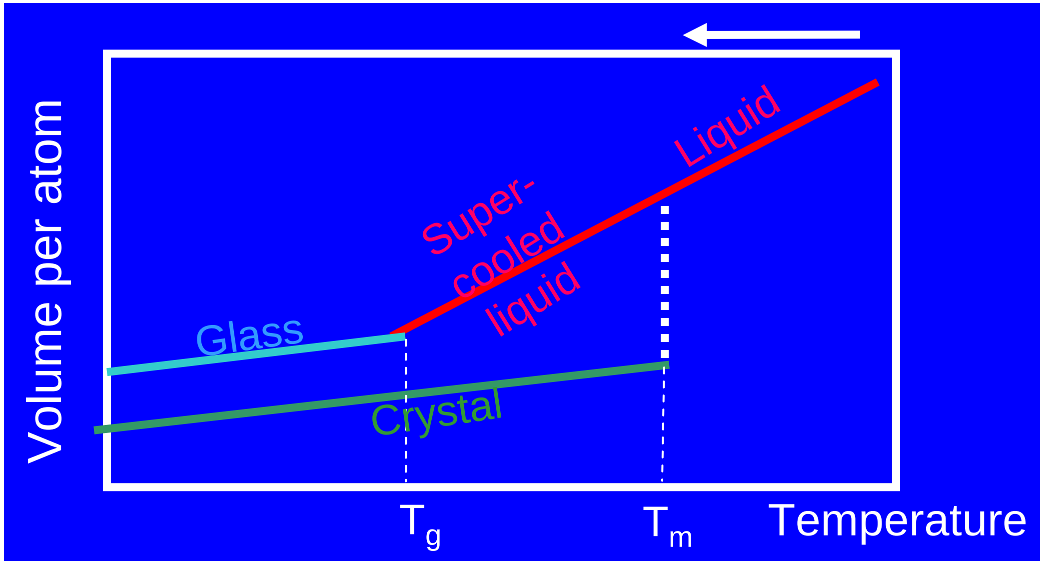


Maximum ejection force

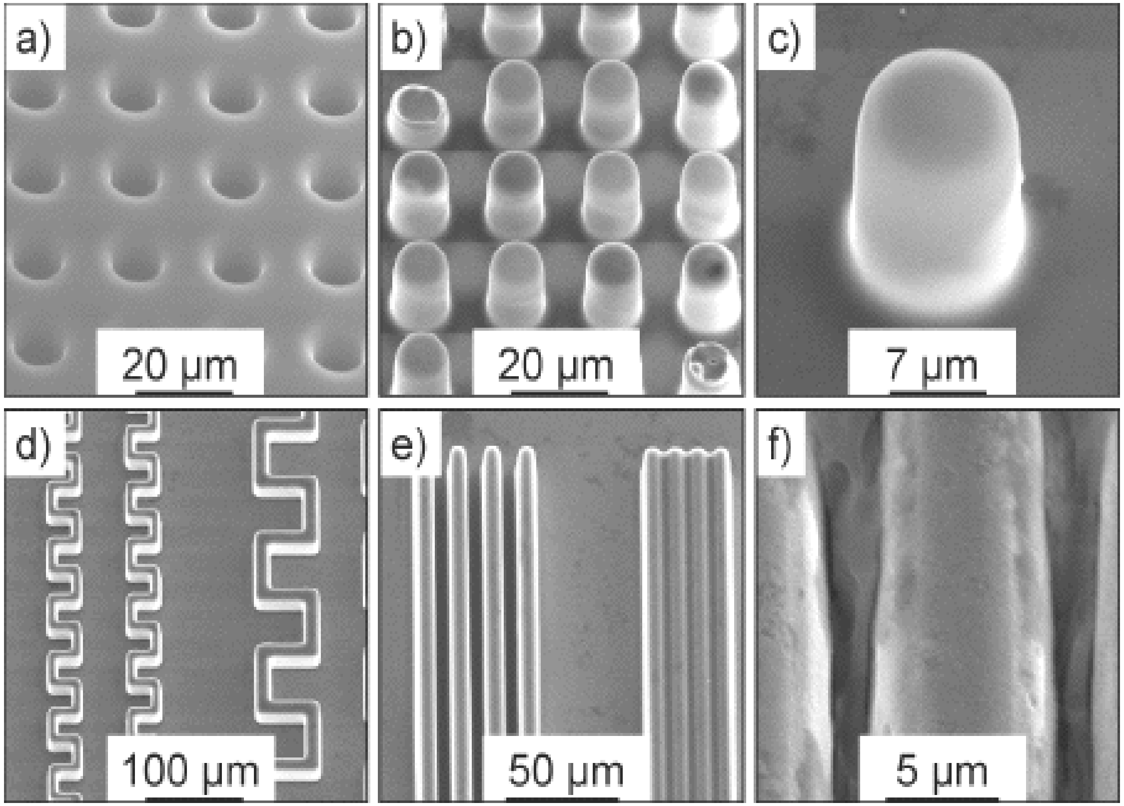


Shaping of BMG by pressing or casting



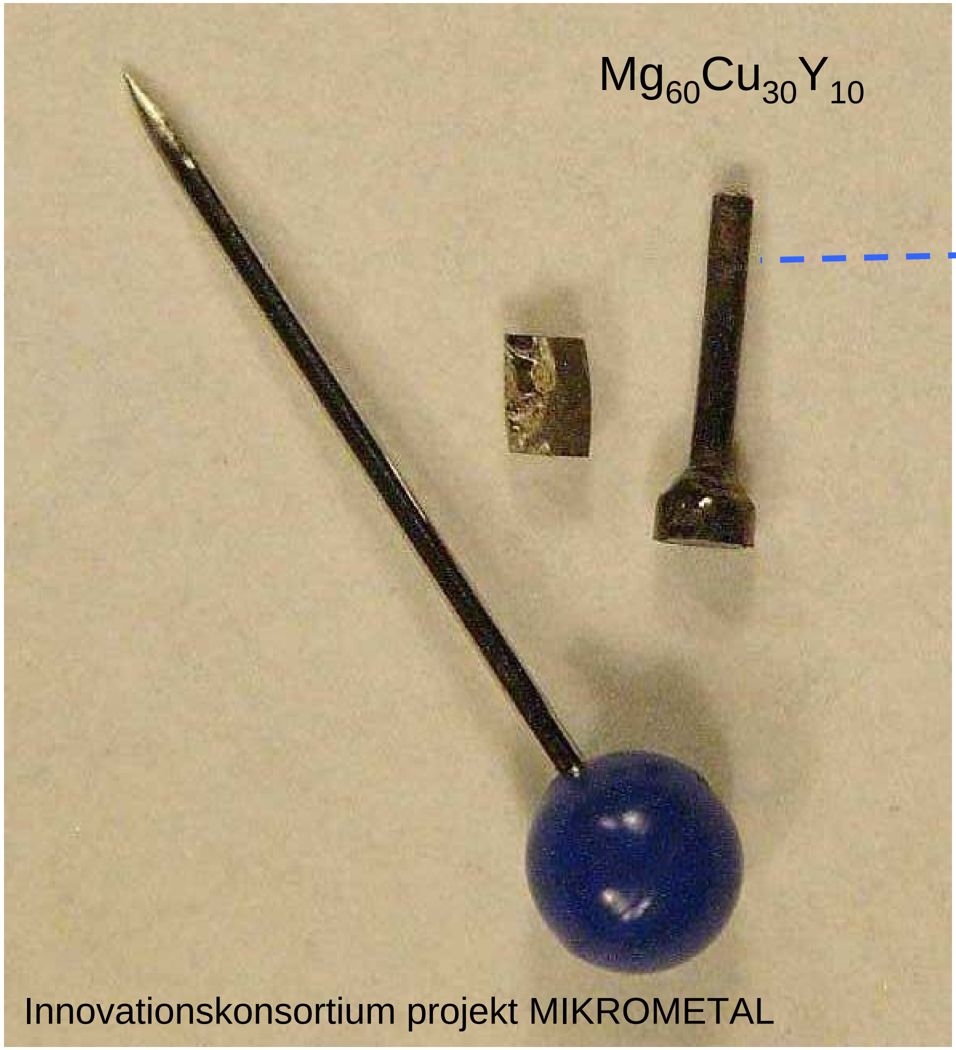


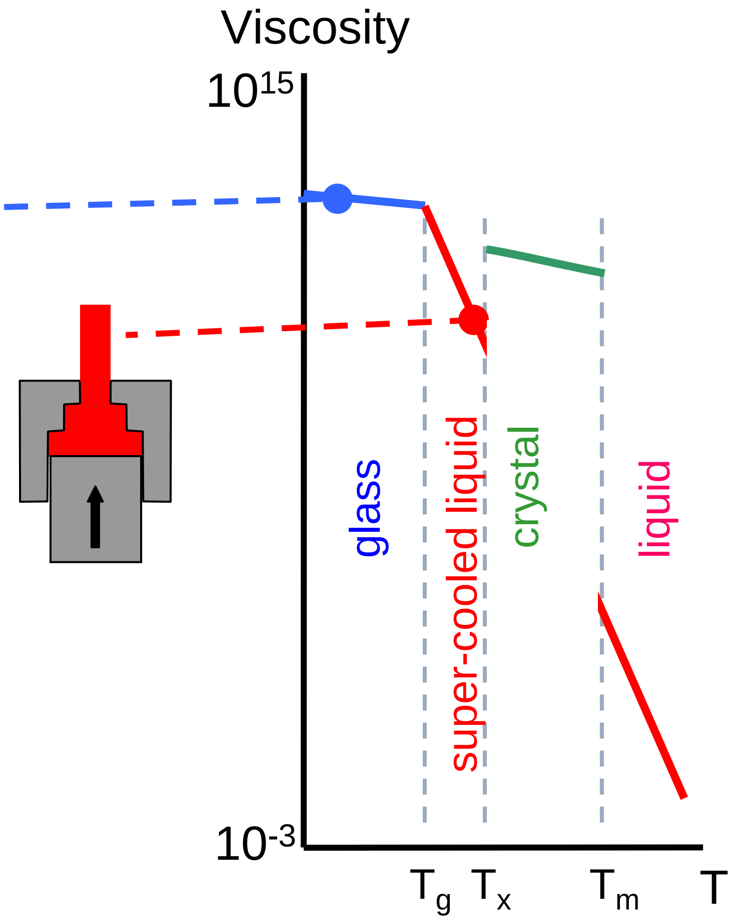
Casting



- to near net-shape

Extrudet microcomponent (10 mm – 10 µm)





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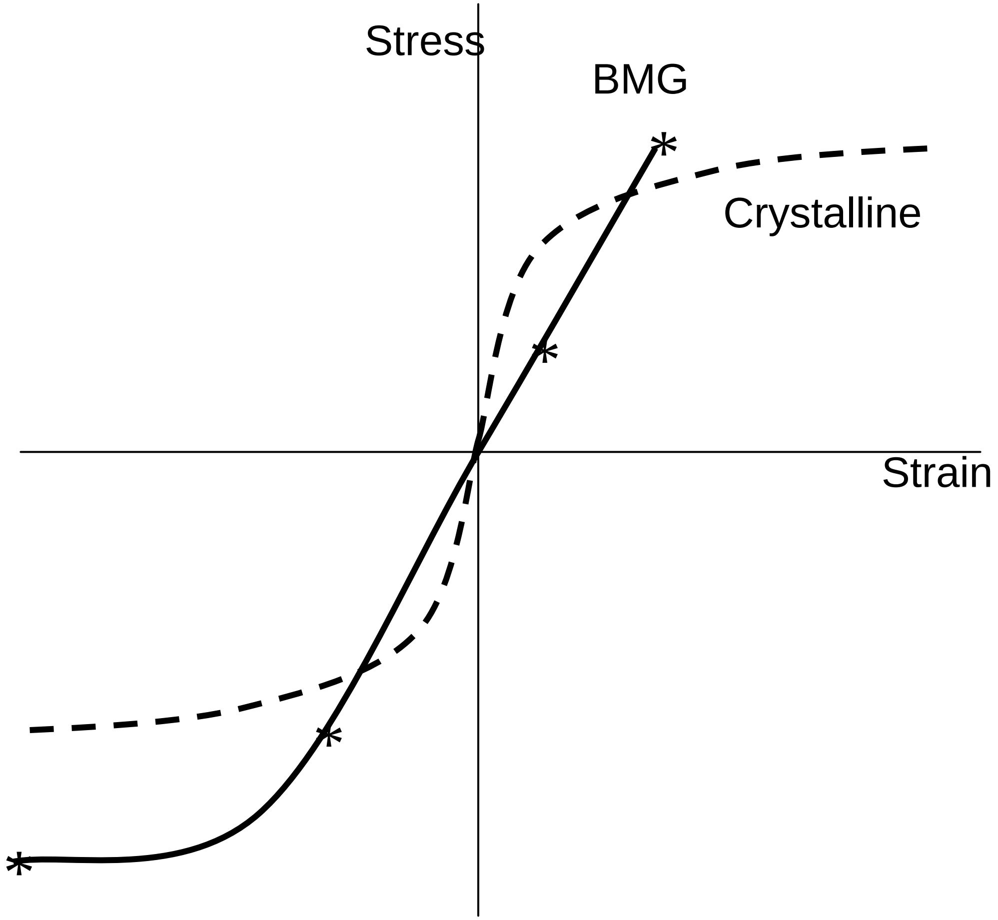
Characteristic BMG properties below T_g



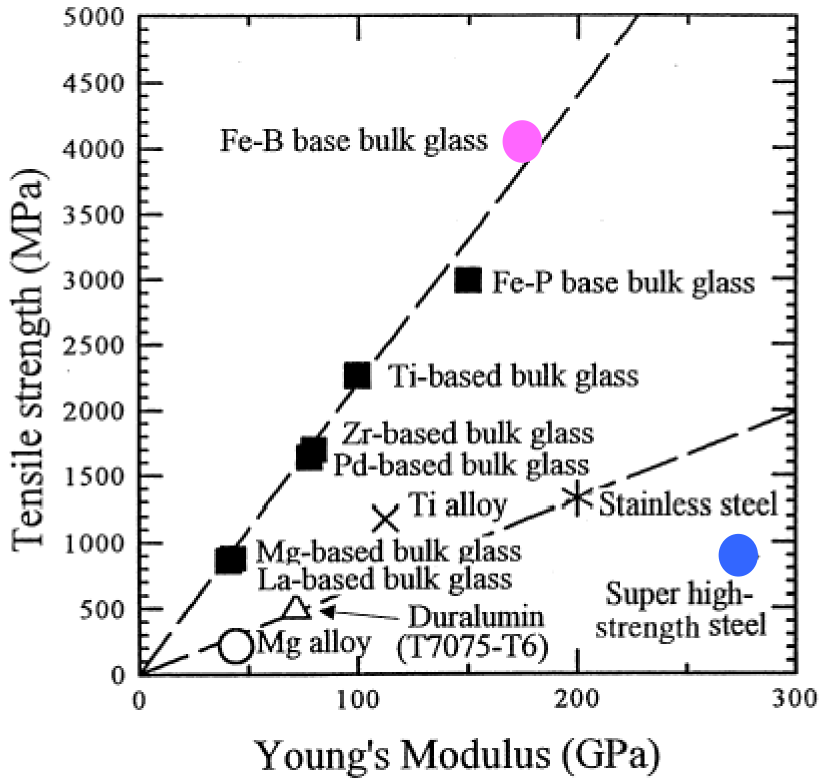
Modulus ca. 40% of cryst. alloy

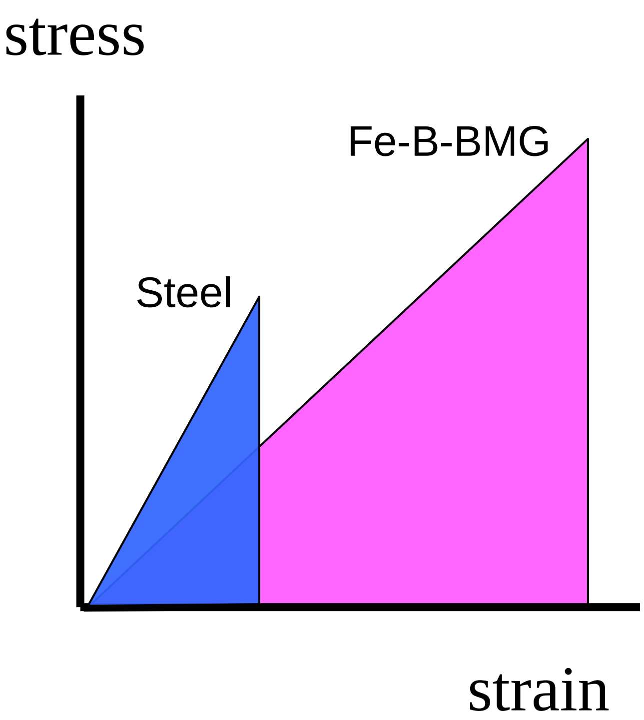
Virtually no plastic flow in tension

Fracture stress in tension (*) depends on BMG and quality of casting

0 - several % plastic flow in compression

Elastic Modulus





Energy Storage Comparison

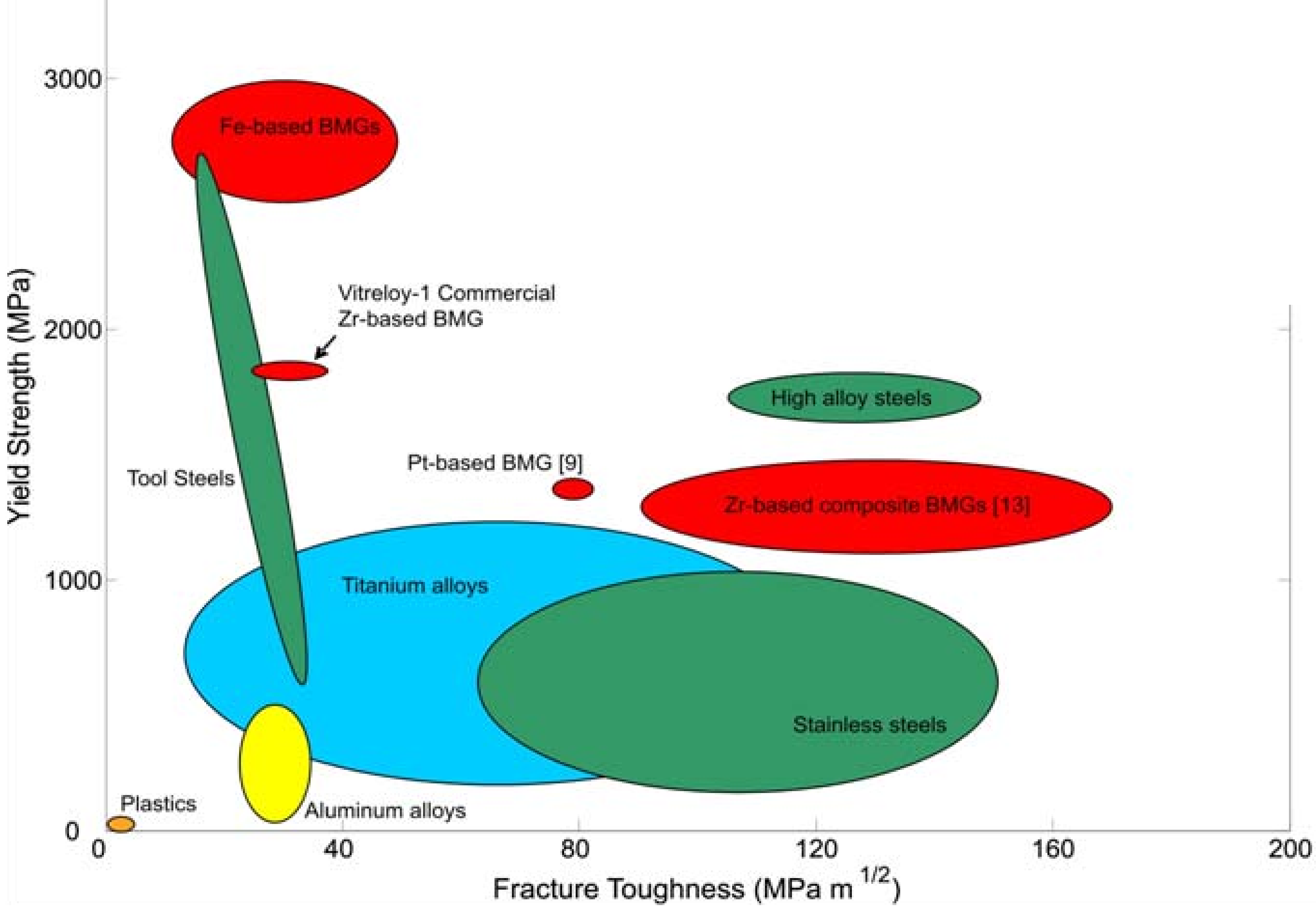
Medium	kW h / kg
Hydrogen	38
Gasoline	14
Dynamite	1.2
Carbon fiber flywheel	0.2
Steel flywheel	0.05
Lead-acid battery	0.04
Amorphous Fe spring	0.005
Steel spring	0.001

Mechanical properties at room temperature

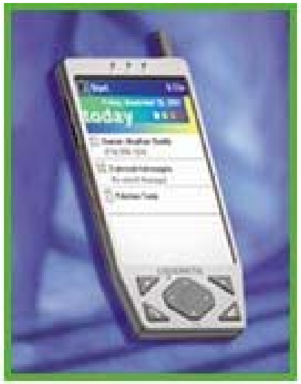
Properties	$Mg_{60}Cu_{30}Y_{10}$	$Zr_{55}Cu_{20}Ni_{10}Al_{15}$	$Zr_{44}Cu_{40}Al_8Ag_8$	$Zr_{41.2}Be_{22.5}Ti_{13.8}Cu_{12.5}Ni_{10}$ Vitreloy1	$Zr_{44}Ti_{11}Cu_{10}Ni_{10}Be_{25}$ Vitreloy 1B	$Zr_{58.5}Cu_{15.6}Ni_{12.8}Al_{10.3}Nb_{2.8}$ Vitreloy 106	$Pt_{57.5}Cu_{14.7}Ni_{5.3}P_{22.5}$	$Fe_{48}Cr_{15}Mo_{14}Er_2C_{15}B_6$
E, GPa	70	90	115 [7]	96	96.7	87.3[6]	94.8	213
G, GPa	(25)	32		37.4	35.6	31.9[6]	33.3	81[4]
Yield strength, compression, MPa	850	1810[2]	1900	1900	1860	1820	1470	3750[4]
Plastic strain at fracture, compression	0.007%	0.2%[2]	0.1[7]	0	0	0.5%	~20%	0
Fracture strength tension, MPa	ca. 600	1760[1]		1800	1800	1200		
Plastic strain at fracture, tension	0%	0%[1]				0%		
Vickers hardness, GPa	4.3	5.5		5.4	5	5.9[6]	4.02	13[5]
Fracture toughness, MPa $m^{1/2}$		43[3]	17[7]	55			80	12.7 ± 4.1

1. $Zr_{52.5}Ti_5Cu_{17.9}Ni_{14.6}Al_{10}$ 2. $Zr_{58}Ni_{13.6}Cu_{18}Al_{10.4}$ 3. $Zr_{55}Cu_{30}Ni_5Al_{10}$ 4. $Fe_{49}Cr_{15}Mo_{14}C_{15}B_6Er_1$ 5. $Fe_{48}Cr_{15}Mo_{14}C_{15}B_6$ 6. $Zr_{57}Nb_5Cu_{15.4}Ni_{12.6}Al_{10}$ 7. $Zr_{48}Cu_{36}Al_8Ag_6$

Comparison of mechanical properties for some BMGs with conventional alloys



Head®Liquidmetal®Radical Racquet



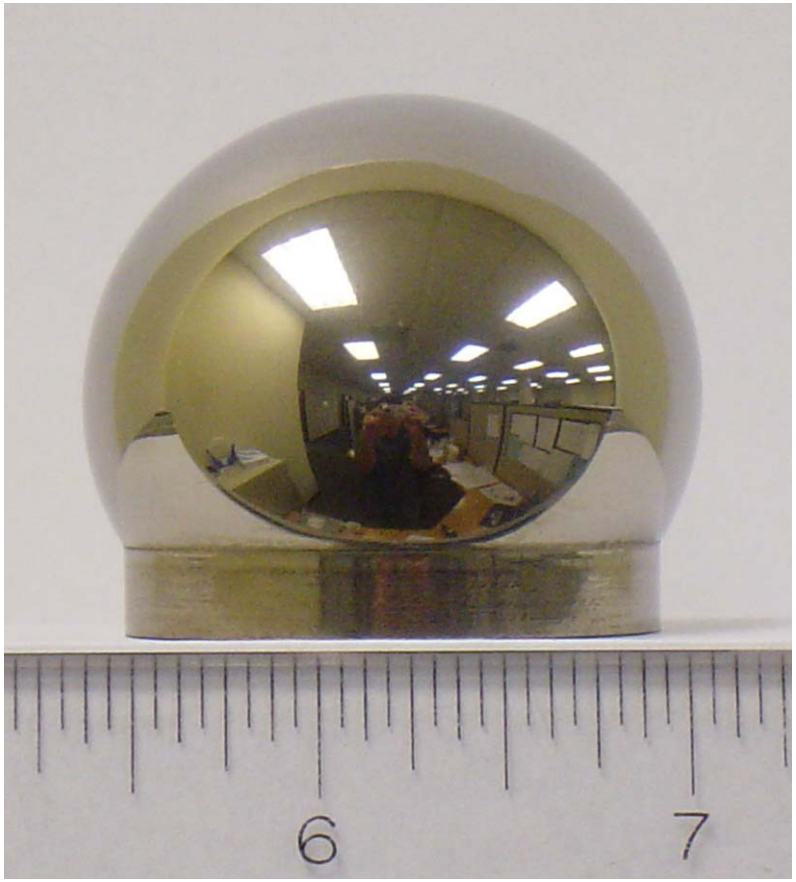
LIQUIDMETAL®

BLOW-MOLDING

$Zr_{44}Ti_{11}Cu_{10}Ni_{10}Be_{25}$

T=460°C, t =100 sec

Lung power, ~10^4 Pa



T=460°C, t =40 sec

10^5 Pa, 400% strain

Schroers et al. 2008

The unique characteristic of all BMG is the tremendous softening that occurs abruptly above T_g

- Microcomponent and microdevice shaping
- Faithful replication down to nm sizes (dependent on aspect ratio)
- Smooth surfaces

- Each BMG is an individual material with its own characteristics
- No BMG has all desirable characteristics: hard, strong, fatigue resistant, corrosion resistant, extremely formable, cheap, …
- No known BMG exhibits plastic strain in unconstrained tension
- All BMG contain at least 3 elements, composition is not very flexible

Thanks for collaboration with colleagues at Risø DTU

and participants in the innovation consortium MIKROMETAL:

DTU Mekanik